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LOW LOSS SYNCERONOUS RECTIFIER  
FOR APPLICATION TO CLAMPED-MODE  
POWER CONVERTERS

[ This application is a continuation in part of application  
Ser. No. 08/054,918 filed on Apr. 29, 1993 now issued as  
U.S. Pat. No. 5,303,138 on Apr. 12, 1994. ]

FIELD OF THE INVENTION

This invention relates to switching type power converters  
and in particular to forward and flyback converters having a  
clamp-mode topology.

BACKGROUND OF THE INVENTION

Self synchronized rectifiers refer to rectifiers using MOS-  
FET rectifying devices having control terminals which are  
driven by voltages of the windings of the power transformer  
in order to provide the rectification of the output of the  
transformer. Use of synchronous rectifiers has been limited  
however by the inefficiency of these rectifiers in buck  
derived converter topologies. Efficiency is limited due to the  
nature of switching of buck derived converters (i.e. buck,  
buck-boost, boost converters including forward and flyback  
topologies) and due to the variability of the transformer reset  
voltages in the forward type converters. This variability of  
reset voltage limits the conduction time of one of the  
MOSFET rectifiers, diminishing the effectiveness and effi-  
ciency of the rectifier. This is because the rectifying devices  
do not conduct for the full switching period and the gate  
drive energy of one of the rectifiers is dissipated.

SUMMARY OF THE INVENTION

A synchronous rectifier is combined with a clamped-mode  
buck derived power converter. In one illustrative embodi-  
ment a hybrid rectifier includes a MOSFET rectifying device  
active in a first cyclic interval of the conduction/noncon-  
duction sequence of the power switch. A second rectifying  
device embodied in one illustrative embodiment as a low  
forward voltage drop bipolar diode rectifying device is  
active during an alternative interval to the first conduction/  
nonconduction interval. The gate drive to the MOSFET  
device is maintained continuous at a constant level for  
substantially the all of the second interval by the clamping  
action of the clamping circuitry of the converter. This  
continuous drive enhances the efficiency of the rectifier.

The bipolar rectifier device may also embodied as a  
MOSFET device in a rectifier using two MOSFET devices.  
The subject rectifier may be used in both forward and  
flyback power converters.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 is a schematic of a forward converter, of the prior  
art, having a synchronous rectifier;

FIG. 2 is a voltage waveform of the secondary trans-  
former winding of the converter of FIG. 1;

FIG. 3 is a schematic of a clamped-mode forward con-  
verter with a synchronous rectifier embodying the principles  
of the invention;

FIG. 4 is a voltage waveform of the secondary trans-  
former winding of the converter of FIG. 3;

FIG. 5 is a schematic of another version of a clamped-  
mode forward converter with a synchronous rectifier  
embodying the principles of the invention;

FIG. 6 is a schematic of another version of a clamped-mode forward converter with a synchronous rectifier and a center tapped secondary winding embodying the principles of the invention;

5 FIG. 7 is a schematic of a clamped-mode flyback converter with a synchronous rectifier embodying the principles of the invention; and

10 FIG. 8 is a schematic of another version of a clamped-mode forward converter with a synchronous rectifier and a center tapped secondary winding embodying the principles of the invention.

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#### DETAILED DESCRIPTION

15 In the converter shown in the FIG. 1, a conventional forward topology of the prior art with an isolating power transformer is combined with a self synchronized synchronous rectifier. In such a rectifier controlled devices are used with the control terminals being driven by an output winding of the power transformer.

20 A DC voltage input  $V_{in}$  at input 100, is connected to the primary winding 110 of the power transformer by a MOSFET power switch 101. The secondary winding 102 is connected to an output lead 103 through an output filter inductor 104 and a synchronous rectifier including the MOSFET rectifying devices 105 and 106. Each rectifying device includes a body diode 108 and 107, respectively.

25 With the power switch 101 conducting, the input voltage is applied across the primary winding 110. The secondary winding 102 is oriented in polarity to respond to the primary voltage with a current flow through the inductor 104, the load connected to output lead 103 and back through the MOSFET rectifier 106 to the secondary winding 102. Continuity of current flow in the inductor 104, when the power switch 101 is non-conducting, is maintained by the current path provided by the conduction of the MOSFET rectifier 105. An output filter capacitor 111 shunts the output of the converter.

30 Conductivity of the MOSFET rectifiers is controlled by the gate drive signals provided by the voltage appearing across the secondary winding 102. This voltage is shown graphically by the voltage waveform 201 in FIG. 2. During the conduction interval  $T_1$  of the power switch 101, the secondary winding voltage  $V_{ns1}$  charges the gate of MOSFET 106 to bias it conducting for the entire interval  $T_1$ . The MOSFET 105 is biased non conducting during the  $T_1$  interval. The conducting MOSFET rectifying device 106 provides the current path allowing energy transfer to the output during the interval  $T_1$ . The gate of MOSFET rectifier 106 is charged in response to the input voltage  $V_{in}$ . All of the gate drive energy due to this voltage is dissipated.

35 As the power MOSFET switch 101 turns off, the voltage  $V_{ns1}$  across the secondary winding 102 reverses polarity just as the time interval  $T_2$  begins. This voltage reversal initiates a reset of the transformer magnetizing inductance, resonantly discharges the gate of MOSFET rectifier 106 and begins charging the gate of MOSFET rectifier 105. As shown by the voltage waveform of FIG. 2, the voltage across the secondary winding 102 is not a constant value, but is rather a variable voltage that collapses to zero in the subsequent time interval  $T_3$ , which occurs prior to the subsequent conduction interval of the power switch 101. This voltage is operative to actually drive the rectifier 105 conducting over only a portion of the time interval  $T_2$  which is indicated by the cross hatched area 202 associated with the waveform 201 in FIG. 2. This substantially diminishes the

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performance of the rectifier 105 as a low loss rectifier device. This is aggravated by the fact that the body diode 108 of the rectifier 105 has a large forward voltage drop which is too large to efficiently carry the load current.

The loss of efficiency of the synchronous rectifier limits the overall efficiency of the power converter and has an adverse effect on the possible power density attainable. Since the synchronous rectifier 105 does not continuously conduct throughout the entire switching period, a conventional rectifier diode (e.g. connected in shunt with rectifier 105) capable of carrying the load current is required in addition to MOSFET rectifier 105. This inefficiency is further aggravated by the gate drive energy dissipation associated with the MOSFET rectifier 106. This gate drive loss may exceed the conduction loss for MOSFET rectifier 106, at high switching frequency (e.g. >300 kHz).

The efficiency of a forward converter with synchronous rectification is significantly improved according to the invention by using a clamp circuit arrangement to limit the reset voltage and by using a low forward voltage drop diode in the rectifying circuitry. Such an arrangement is shown in the schematic of FIG. 3. In this forward power converter the power MOSFET device 101 is shunted by a series connection of a clamp capacitor 321 and a MOSFET switch device 322. The conducting intervals of power switch 101 and MOSFET device 322 are mutually exclusive. The duty cycle of power switch 101 is D and the duty cycle of MOSFET device 322 is 1-D. The voltage inertia of the capacitor 321 limits the amplitude of the reset voltage appearing across the magnetizing inductance during the non conducting interval of the MOSFET power switch 101.

The diode 323 of the synchronous rectifier, shown in FIG. 3, has been substituted for the MOSFET device 106 shown in the FIG. 1. Due to the dissipation of gate drive energy the overall contribution of the MOSFET rectifier 106 in FIG. 1 is limited. The clamping action of the clamping circuitry results in the constant voltage level 402 shown in the voltage waveform 401, across the secondary winding 102, in the time period  $T_2$ . This constant voltage applied to the gate drive of the MOSFET rectifier 105 drives it into conduction for the entire  $T_2$  reset interval. In this arrangement there is no need for a bipolar or a body diode shunting the MOSFET rectifier 105. An advantage in the clamped mode converter is that the peak inverse voltage applied to the diode 323 is much less than that applied to the similarly positioned MOSFET device in FIG. 1. Accordingly the diode 323 may be a very efficient low voltage diode which may be embodied by a low voltage diode normally considered unsuitable for rectification purposes.

In the operation of the clamped mode forward converter the MOSFET switch 322 is turned off just prior to turning the MOSFET power switch on. Energy stored in the parasitic capacitances of the MOSFET switching devices 101 and 322 is commutated to the leakage inductance of the power transformer, discharging the capacitance down toward zero voltage. During the time interval  $T_3$  shown in FIG. 4, voltage across the primary winding is supported by the leakage inductance. The voltage across the secondary winding 102 drops to zero value as shown in the FIG. 4. With this zero voltage level of the secondary winding, the output inductor resonantly discharges the gate capacitance of the MOSFET rectifying device 105 and eventually forward biases the bipolar diode 323. The delay time  $T_3$  is a fixed design parameter and is a factor in the control of the power switches 101 and 322, which may be switched to accommodate soft waveforms. This synchronous rectification circuit of FIG. 3 provides the desired efficiencies lacking in the arrangement of the circuit shown in FIG. 1.

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Control of the conductivity of the power switching devices 101 and 322 is by means of a control circuit 350, which is connected, by lead 351, to an output terminal 103 of the converter to sense the output terminal voltage. The control circuit 350 is connected, by leads 353 and 354, to the drive terminals of the power switches 101 and 322. The drive signals are controlled to regulate the output voltage at output terminal. The exact design of a control circuit, to achieve the desired regulation, is well known in the art and hence is not disclosed in detail herein. This control circuit 350 is suitable for application to the converters of FIGS. 5, 6, 7 and 8.

A modified version of the circuit of FIG. 3 is shown in the circuit schematic of the FIG. 5. The converter of FIG. 5 is a clamped mode forward converter having two gated synchronous rectifying devices 105 and 106. In this embodiment of the synchronous rectifier the synchronized rectifying device 106 can be used without adversely affecting the converter efficiency at lower operating frequencies.

The circuit of FIG. 6 is a clamped mode forward converter having a rectifier analogous to that of FIG. 3 in using one bipolar rectifying diode. The secondary winding is tapped creating two secondary winding segments 603 and 602.

The converter of FIG. 7 operates in a flyback mode. The bipolar and synchronous rectifier device are in a reversed connection from the connection of FIG. 3 to accommodate the flyback operation.

In some applications direct application of the gate drive signal directly from the secondary winding may result in voltage spikes exceeding the rating of the gate. A small signal MOSFET device 813 is connected to couple the gate drive to the MOSFET rectifying device 105. This device may be controlled by the control drive lead 815 to limit the peak voltage applied to the gate of rectifier 105. The MOSFET synchronous rectifier is then discharged through the body diode of the MOSFET device 813.

CM I claim:

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In a power converter, comprising:  
 an input for accepting a DC voltage;  
 a power transformer including a primary and secondary winding;  
 a power switch for periodically connecting the input to the primary winding;  
 an output for accepting a load to be energized;  
 clamping means for limiting a voltage and extending the voltage's duration across the secondary winding at a substantially constant amplitude during substantially an entire extent of a clamping interval of a cyclic period of the power converter;  
 a rectifier circuit connecting the secondary winding to the output; and including:  
 a synchronous rectification device with a control terminal connected to be responsive to a signal across the secondary winding such that the synchronous rectification device conducts a load current during substantially the entire extent of the clamping interval; and  
 a rectifying device connected for enabling conduction of the load current during a second interval other than the clamping interval.]

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2. In a power converter, comprising  
 an input for accepting a DC voltage;  
 a power transformer including a primary and secondary winding;  
 a power switch for periodically connecting the input to the primary winding during a second interval of a cyclic period;  
 an output for accepting a load to be energized;  
 clamping means for limiting a voltage and extending the voltage's duration across the secondary winding at a substantially constant amplitude during substantially an entire extent of a clamping interval of a cyclic period of the power converter;  
 a rectifier circuit connecting the secondary winding to the output; and including:  
 a first synchronous rectification device with a control terminal connected to be responsive to a signal across the secondary winding such that the synchronous rectification device conducts a load current during substantially the entire extent of the clamping interval, and  
 a second synchronous rectification device with a control terminal connected to be responsive to a signal across the secondary winding such that the second synchronous rectification device conducts the load current during substantially an entire extent of the second interval other than the clamping interval.]

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[3. In a power converter as claimed in claim 1 or 2, comprising:  
 the converter connected to operate as a forward type converter.]  
 [4. In a power converter as claimed in claim 1 or 2, comprising:  
 the converter connected to operate as a flyback type converter.]  
 [5. A switching mode power converter, comprising:  
 a power transformer including a magnetizing inductance requiring periodic recycling;  
 a first power stage for converting a DC input into a periodic pulsed voltage applied to a primary winding of the transformer, including:  
 a clamping circuit for limiting a voltage of the transformer during the periodic recycling at a substantially constant amplitude and extending the voltage duration to maintain a constant voltage for substantially an entire extent of periodic recycling;

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a second power  
power stage for rectifying an output of a sec-  
ondary winding of the transformer and applying it to a  
load to be energized, including:

a synchronous rectifier including a first rectifying  
device with a control gate connected to be responsive  
to a signal across the secondary winding such that  
the synchronous rectification device conducts a load  
current during the periodic recycling when the  
clamping circuit is active, and

a second rectifying device connected for enabling con-  
duction of the load current when the first rectifying  
device is nonconducting.]

[6. A switching mode power converter as claimed in claim  
5, further comprising:

the second rectifying device comprises a diode.]

[7. A switching mode power converter as claimed in claim  
5, further comprising:

the second rectifying device comprises a rectifying device  
with a control gate connected to be responsive to a  
signal of the secondary winding.]

[8. A switching mode power converter as claimed in claim  
6 or 7, further comprising:

the secondary winding tapped and separated into first and  
second winding segments, and the first rectifying  
device is connected to the first winding segment and the  
second rectifying device is connected to the second  
winding segment.]

[9. A switching mode power converter as claimed in claim  
6 or 7, further comprising:

the converter connected to operate as a forward type  
converter.]

[10. A switching mode power converter as claimed in  
claim 6 or 7, further comprising:

the converter connected to operate as a flyback type  
converter.]

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